AFCRL-442

STRUCTURAL-STRATIGRAPHIC STUDIES ON THE WARD HUNT ICE SHELF

John B. Lyons
Frank G. Leavitt

Dartmouth College: Hanover, N. H.

Final Report
Contract AF19(604)-6188

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Prepared for

GEOPHYSICS RESEARCH DIRECTORATE
AIR FORCE CAMBRIDGE RESEARCH LABORATORIES
OFFICE OF AEROSPACE RESEARCH
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ABSTRACT

Reexamination of the stratigraphy of the Ward Hunt Ice Shelf suggests that its uppermost iced-firn and lake ice unit may overlie two different types of "basement": (1) an older inner basement, 4 to 5 miles wide consisting partly of iced firn, but with a much larger proportion of sea or fresh-water ice than originally described by Marshall (1960), and (2) an outer younger basement, up to 7 miles wide, and consisting of sea ice. The younger basement, as well as the entire outer portion of the Ward Hunt Shelf, is probably less than 1600 years old; the inner basement is probably 1600 to 3000 years old (Crary, 1960).

Deformation of the shelf has proceeded in two stages. An earlier period of folding of the coastal portions of the shelf accompanied a minor glaciation somewhat older than 1600 years. Subsequent to the development of an unconformity and the accumulation of the upper stratigraphic shelf unit, differential ablation has caused the shelf edge to curl up by approximately 2^{o}; broad-scale synclines, cross-folds, and domes have been formed by the same process.

The preferred theory of the origin of the rolls in the Ellesmere shelf is that they were initiated as "hedges" of sea ice, but have been greatly modified by subsequent drainage adjustments during the later build up and latest ablation cycle of the shelf's history. The bottom side of the shelf appears to be broadly, rather than locally, compensated.

The minor glacial cycle responsible for the early deformation of the Ward Hunt shelf has left a conspicuous trim line along northern Ellesmere Island, and fluvio-glacial deposits. Three terrace levels have been developed in Camp Creek within the past 1600 years.

Observations on the bedrock geology confirm and amplify some of the previous deductions of Christie (1957).

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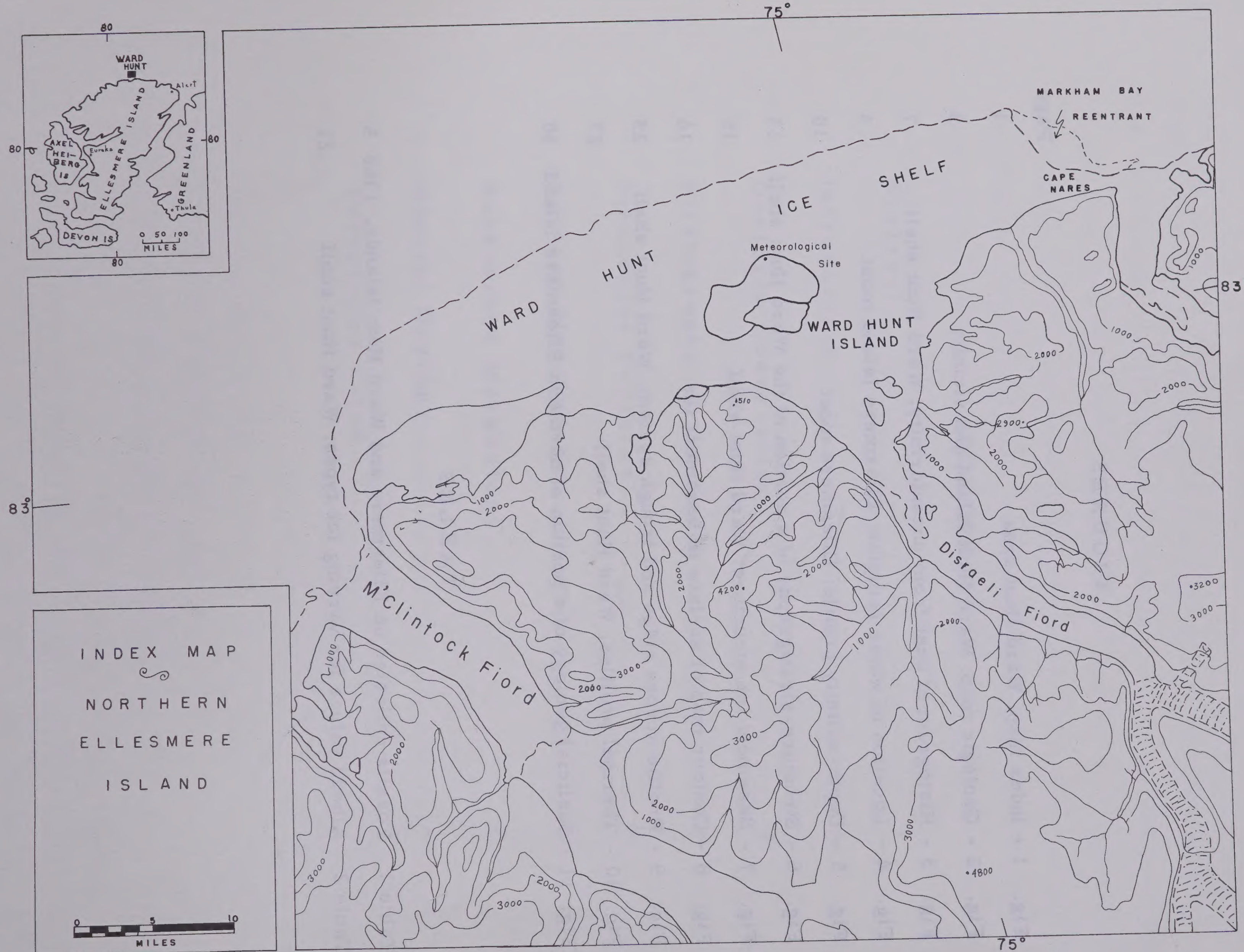

Figure 1 Index map of northern Ellesmere Island and Ward Hunt Ice Shelf

STRUCTURAL-STRATIGRAPHIC STUDIES ON THE
WARD HUNT ICE SHELF

Introduction

This paper summarizes results of studies carried out on the Ward Hunt Ice Shelf (Fig. 1) during the 1960 field season under the auspices of Air Force Cambridge Research Laboratories. Information on the physical characteristics and history of the shelf has previously been published by Hattersley-Smith (1955; 1956 a, b, c; 1957 a, b), Crary (1956, 1958, 1960), Marshall (1955, 1960), and Christie (1957). Reliance upon their results will be obvious throughout much of the following discussion.

Geologic Observations

The information presented in the map of Figure 2 is somewhat more detailed than that shown by Christie (1957) in the area about Ward Hunt Island. The following comments amplify some of his geologic deductions.

The non-fossiliferous M'Clintock Group of volcanics, slate and graywacke has been assigned by Christie (1957, p. 12) to the pre-Middle Ordovician because it appears to be overlain by the Middle and Upper Ordovician Challenger Group of gray limestones and red impure sandstones. Some imperfect orthid (?) brachiopods (first noted by Mr. Dale Well) in graywackes of the M'Clintock formation have been collected from talus on the Ward Hunt Shelf, near the mainland moat. Although they were not discoverable in situ, there is no question as to their origin. Their recognition strongly supports the suggested Ordovician age for this formation.

The areas mapped as the Challenger Group (?) in Figure 2 are underlain by a thickness of at least 120 meters of gray, vuggy, buff-weathering dolomitic limestone. Poorly preserved and tentatively identified specimens of the gastropod Maclurites sp. suggest an Ordovician age for these rocks. Stratigraphic relations to the M'Clintock Group are uncertain; in one area

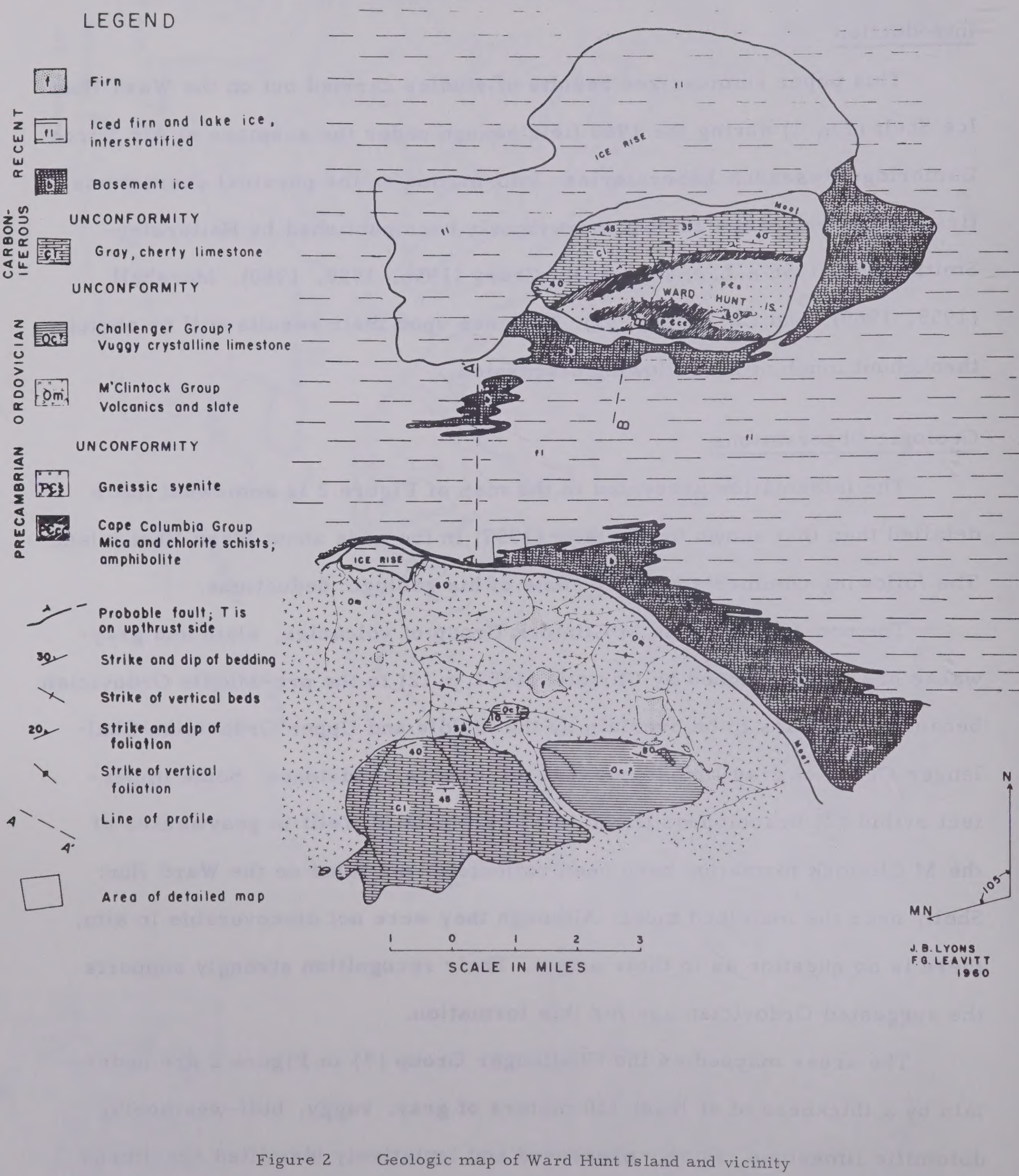

Figure 2 Geologic map of Ward Hunt Island and vicinity

the Challenger Group (?) seemingly dips beneath graywackes of that M'Clintock formation, but in another it apparently rests unconformably above it. Because of these uncertainties it is not clear whether the dolomitic limestones should be referred to the Challenger Group, the M'Clintock Group, or the Mount Disraeli Group. The latter assemblage of crystalline limestone and phyllite has uncertain relations with the other two groups (Christie, 1957, p. 11), but presumably lies beneath them.

On the Ellesmere mainland the Permo-Carboniferous limestones have a minimal stratigraphic thickness of more than 1100 meters. The basal 30 meters of the section consists of fanglomerates with angular fragments up to 15 centimeters in maximum dimension, consisting of chlorite schist, granitic gneiss, quartzite, angular quartz fragments, and tan limestone. Above this are 50 meters of red-weathering gray limestone, succeeded by approximately 330 meters of gray, tan, and black limestone, containing very poorly preserved silicified brachiopods and crinoids. In the lower portion of this latter succession, intraformational limestone breccias are common, and in the upper portion, bands of nodular chert. The prolific fossil horizons within the formation commence 490 meters above its base, and continue upward toward the top of the formation. On Ward Hunt Island the Permo-Carboniferous limestones contain no members similar to those in the basal 150 meters of the Ellesmere section. For this reason, it is probable that a northward-dipping (?) fault, rather than a simple angular unconformity, separates the Permo-Carboniferous from the underlying Cape Columbia Group rocks on that island. (cf. Blackadar, 1954, p. 21; Christie, 1957, p. 33).

In Table 1 (below) is a list of the Pennsylvanian-Permian fossils (identified by L. A. Persson of Dartmouth College) which were collected on Ward Hunt and Ellesmere Islands during the 1960 field season. Also indicated, by checks are references to the same identifications by Christie (1957), Blackadar (1954), and Feilden and de Rance (1878) on Ellesmere Island. For com-

parison, we have also listed some of the fossils identified by Harker and Thorsteinsson (1960) in the Lower Permian Assistance Bay formation of Devon Island. The *cleiothyridina subexpansa*, *pterospirifer* sp., and *canina ovibus* are all generally restricted to the Permian and suggest a Permian age for the Ellesmere material. A more definite age assignment may be possible if the fusulinds, now at the Geological Survey of Canada, are identifiable.

Table 1

Fossils Collected on Ellesmere and Ward Hunt Islands, 1960

	Feilden De Rance	Blackadar	Christie	Harker Thorsteinsson
Bryozoa				
Fenestrellina, sp?		x	x	
Rhombocladia?, delicata				
Brachiopods				
Dictyoclostus, neoinflatus	x		x	x
Squamularia, asiatica				x
Cleiothyridina, subexpansa				x
Linoproductus, sp?		x	x	x
Neospirifer, cameratus		x	x	
Pterospirifer, sp. ?				x
Spiriferella, sp. ?			x	x
Echinoconchus, sp. punctatus				x
Corals				
Favosites, limitaris		x		
Canina, ovibus				x
Syringopora, sp. ?		x	x	
Crinoids				
fragments				
Foraminifera				
Fusulinids; sp. unident.				
Gastropods				
Straparolus?				
Trilobites				
Ditomopyge?				
Unident. portion of pygidium				

As noted by Christie (1957) Silurian limestone pebbles containing *halysites*, sp. ? occur in glacial float on Ward Hunt Island; their nearest point of origin would appear to be at least 45 or 60 kilometers to the southeast, in the

United States Range.

Not shown on the map of Fig. 2 because of their small size, are numerous diabase dikes both on Ellesmere and on Ward Hunt Islands. In the latter area they intrude both the Precambrian and the Permo-Carboniferous formations, and their age, therefore, cannot be more precisely determined than post-Permo-Carboniferous.

Stratigraphy of the Shelf

During the 1960 field season, a joint Dartmouth College-Arctic Institute of North America group drilled an 11-meter deep hole through the Markham Bay Reentrant - that portion of the Ward Hunt Ice Shelf which has re-formed since an ice island broke away from the area in 1946 (Koenig et al, 1952, p. 76). In addition, a trough and a ridge were each drilled to depths of 35 meters in the area a mile north of the edge of the Ice Rise, but these holes did not penetrate the total thickness of the shelf. A fourth hole was drilled completely through the Ice Rise near the meteorological station (see Fig. 1), and bottomed in probable till at a depth of 52.2 meters. A detailed study of these ice cores is being carried out by R. H. Ragle, R. B. Blair, and L. E. Persson, and will be reported on separately.

As pointed out by Marshall (1960) two units are easily recognizable on the shelf: (1) a bluish lower unit of well stratified "basement" ice, and (2) a gray-white upper unit of iced firn and interstratified lake ice. Where seen, the contact between these units is generally marked by a layer of aeolian dust (cf. histogram of Fig. 3) up to a few centimeters in thickness. This dust marks an unconformity, and formed in part as a lag concentrate of silty layers originally constituting a part of the basement ice; it represents a cycle of widespread ablation terminating approximately 1600 years ago (Crary, 1960, p. 45). The outcrop pattern of the unconformity (Fig. 2) brings out a broad synclinal downwarp between Ward Hunt and Ellesmere Islands, some

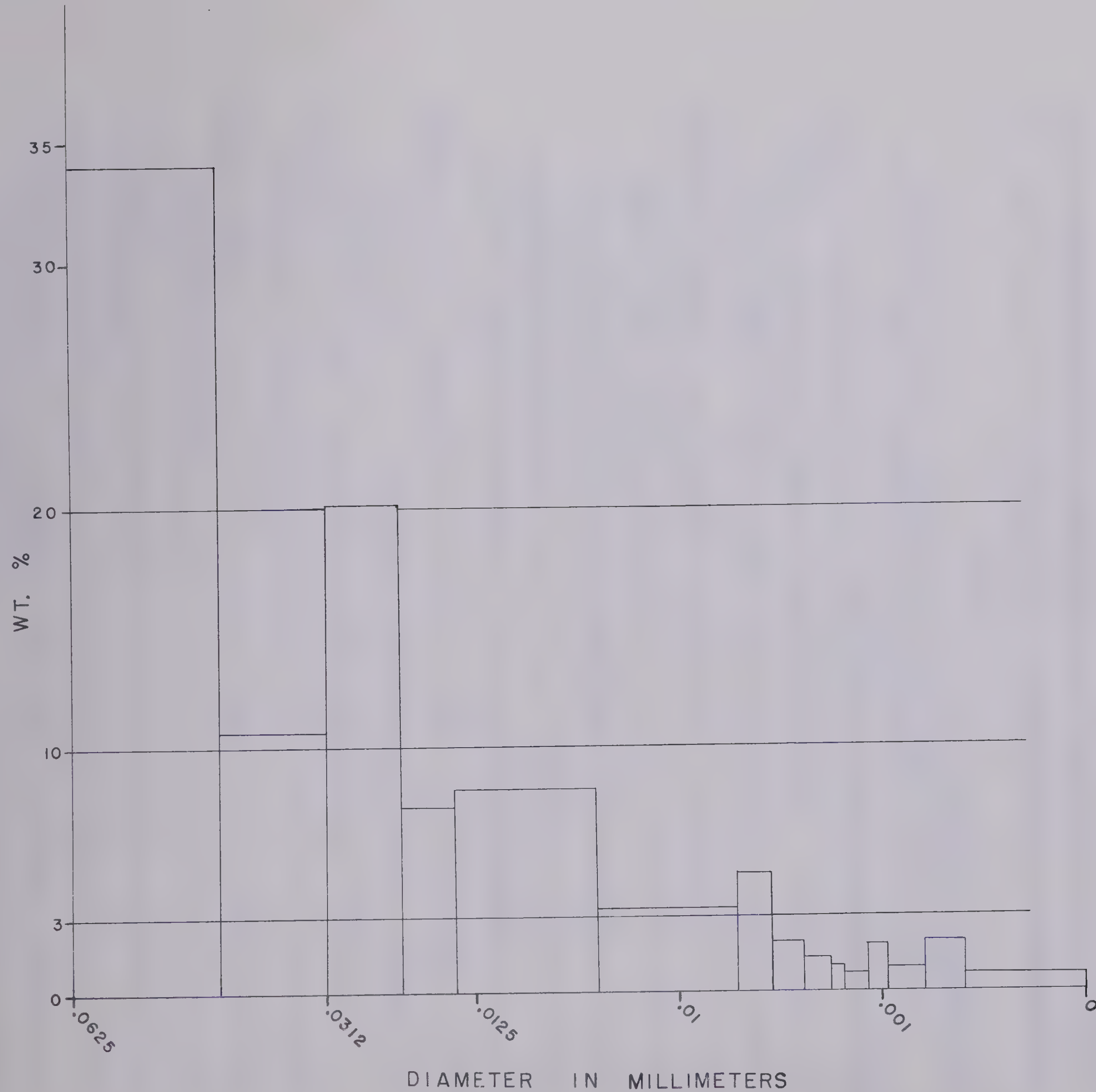

Figure 3 Histogram of dust from the basement-upper ice unconformity; Ward Hunt Shelf

small cross-folds, and a small dome about a mile southwest of the Ward Hunt Ice Rise. The peculiar dentate map pattern in the latter area is due to the intersection of the dome by the ridge-and-trough topography of the shelf.

Three textural types characterize the outcropping basement ice. Very common is columnar ice which has average grain areas (normal to the columns) of 15 cm^2, grain lengths exceeding 25 cm., and long tubular structures (0.1 cm. diameter) formed by migrating gases or liquids. The second variety is finer-grained (average area 0.2 to 2.0 cm^2) and highly inequigranular, often exhibiting sub-parallel crystallographic orientations over broad areas of a thin section. It is characterized by irregularly interdigitating grain boundaries. This ice has been compared by Marshall (1960, p. 46) to sheared glacial ice, but also closely resembles some of the sheared (?) sea ice of the Markham Bay reentrant core now being studied by Ragle and Blair (oral communication). Iced firn is the last and least common variety of basement ice.

Although sea ice was not unquestionably identified in the field, much of the basement ice has a slightly saline taste and Marshall (op. cit.) has therefore concluded that it is brine-soaked. He also believes that the basement is predominantly of glacial origin. It is quite possible, however, that much of the basement may be composed of fresh or brackish water ice, accreted at the bottom of the shelf (cf. Schwarzacher, 1959). Hydrologic investigations in the Ellesmere moat (carried out toward the close of the melt period) showed a sharply defined fresh-salt water interface at a depth of 48 $\pm$ 3 meters (Figs. 4, 5 and 9) - i.e. at a depth of $6\frac{1}{2}$ meters or so below the bottom of the shelf. How far the interface extends seaward beneath the shelf, and what happens to the level of the interface during the freeze season are not known. It is not possible, in the light of our present information, to accurately estimate the relative amounts of glacial and sea (?) ice in the exposed portions of the basement between Ward Hunt and Ellesmere Islands. It is nevertheless

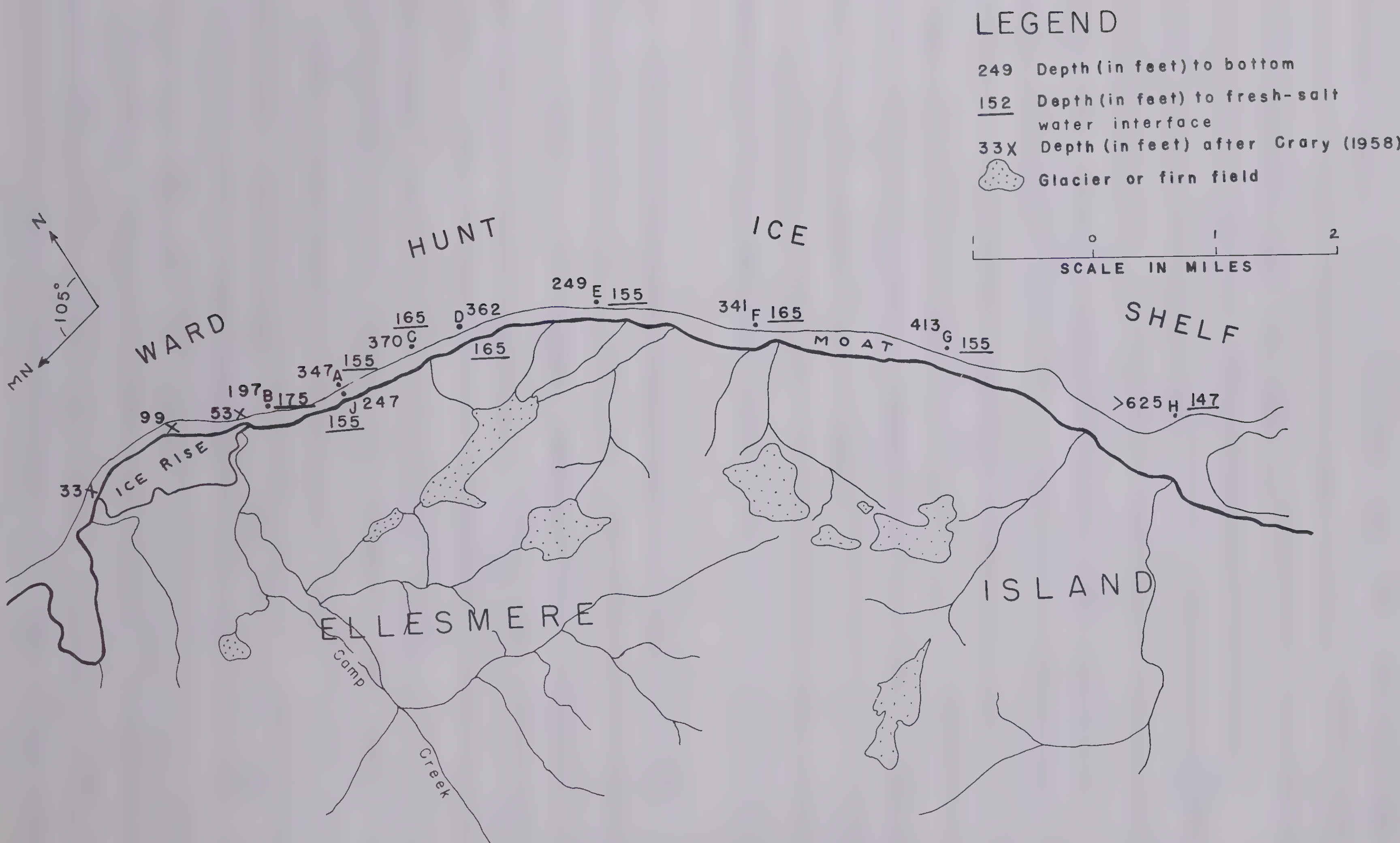

Figure 4 Sketch map showing location of hydrologic stations in the Ellesmere moat

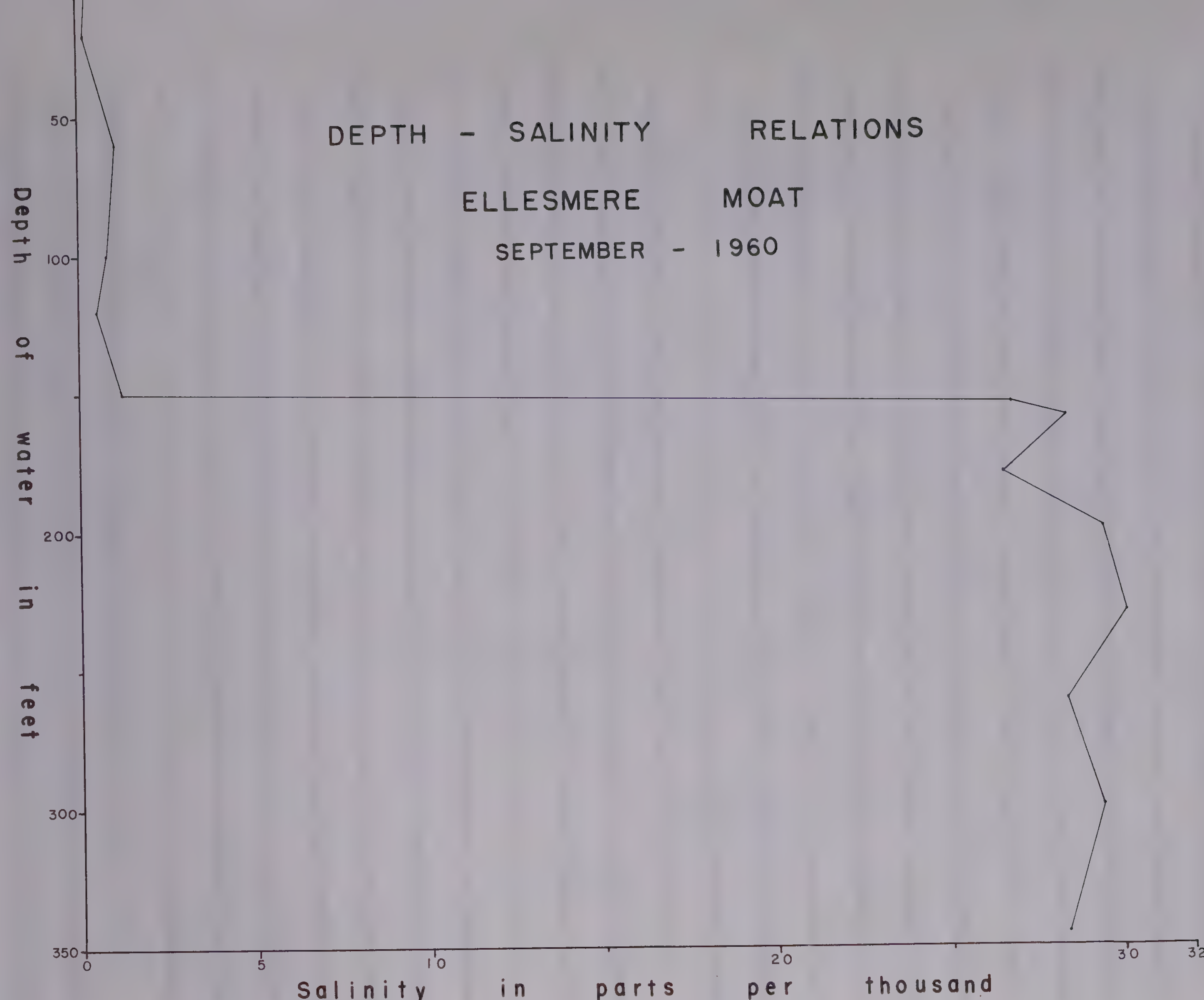

Figure 5 Depth-salinity relations in the Ellesmere moat; September, 1960

quite certain, as will be discussed presently, that the unexposed "basement" north of Ward Hunt is sea ice.

Within the upper ice of the shelf, iced firn and interlensed linear bodies of old lake ice are the major units. Sporadically superimposed on these at the surface (and on the basement as well) are innumerable small pads of what Smith (1960, p. 54) has termed modern lake ice. The latter, because of their high albedo, form small mesa-like pads on the ridges, and thick sheets, up to a few kilometers in length, a hundred meters in width, and a few meters in thickness, occupying some of the trough areas (see Fig. 9). The interrelations of some of the larger old lake ice pads with the iced firn are shown in Figure 6. Other less distinct lake ice units within the iced firn are not shown, but locally constitute up to half of the area mapped as "iced firn and lake ice."

In the upper iced firn of the shelf, Marshall (1960, p. 45-46) has noted what he interprets as an annual cyclic pattern, with units ranging from 12 to 15 cm. in thickness. The top of each unit is characterized by clearer, coarser ice (grain area 1 cm^2) than the bottom (0.2 cm^2 area), and bubble horizons tend to be concentrated at 1 cm. below the top of each unit, at the base of short tubules. The bubble horizons are regarded as the termini of downward-migrating vapor figures, and the coarser-grained ice is thought to be due to more extensive recrystallization. Layers of aeolian dust within the iced firn, when correlated with associated bubble concentrations and vapor figures, are also considered by Marshall to be useful markers of annual accumulation.

The maximum thickness of the upper iced firn and interstratified lake ice between Ward Hunt and Ellesmere Islands is approximately 20 meters (Fig. 9), and is 33 meters at the meterological site on the Ice Rise (Ragle and Blair, oral communication). If Crary's (op. cit.) interpretation of the somewhat inconsistent radiocarbon data is correct, and the upper iced firn

accumulated chiefly in the interval between 1600 and 400 years ago. Its net rate of increment would be between 2 1/2 and 4 cm. per year, or considerably less than the 12 to 15 cm. figure derived by Marshall on stratigraphic grounds. The data are not necessarily in conflict, however, provided one makes the assumption that net ablation fell only slightly short of the net accumulation, on the average, and that the loci of net accumulation were varied from year to year.

In the holes drilled through the Ice Rise, and to depths of 35 meters in the ridge and trough north of the Ice Rice (Ragle and Blair, oral communication) there is no heavy dirt layer separating a blue basement unit from a gray upper unit.

Below a mixed zone of 33 to 39 meters depth in the Ice Rise, iced firn is completely absent (with one questionable exception) and sea ice makes up the bottom 13 (or 19) meters of the section. Sea ice also occurs toward the bottom of the ridge and through cores (Ragle and Blair, oral communication) and presumably, therefore, forms the basal portion of the northern three-fifths of the shelf.

The absence of the heavy dirt layer north of Ward Hunt Island and the uniform sea-ice nature of the basement in this area suggest that during the height of the ablation cycle in which this dirt was lag concentrated, the shelf may not have extended very far north of the island, and may have been reduced to a width of 6 or 8 kilometers. In this event, the later extension of the shelf to a 17 kilometer width would necessarily have coincided with the build-up of the upper iced firn unit of the shelf. The platform for this firn accumulation in the outer 9 to 11 kilometers of the shelf could only have been sea ice. Although admittedly conjectural, this reconstruction of the shelf's history appears to be the best synthesis of our present information on its sub-structure. It is also consistent with the preliminary results of the ice core studies, and with Crowley's (1961) seismic profiles of the shelf.

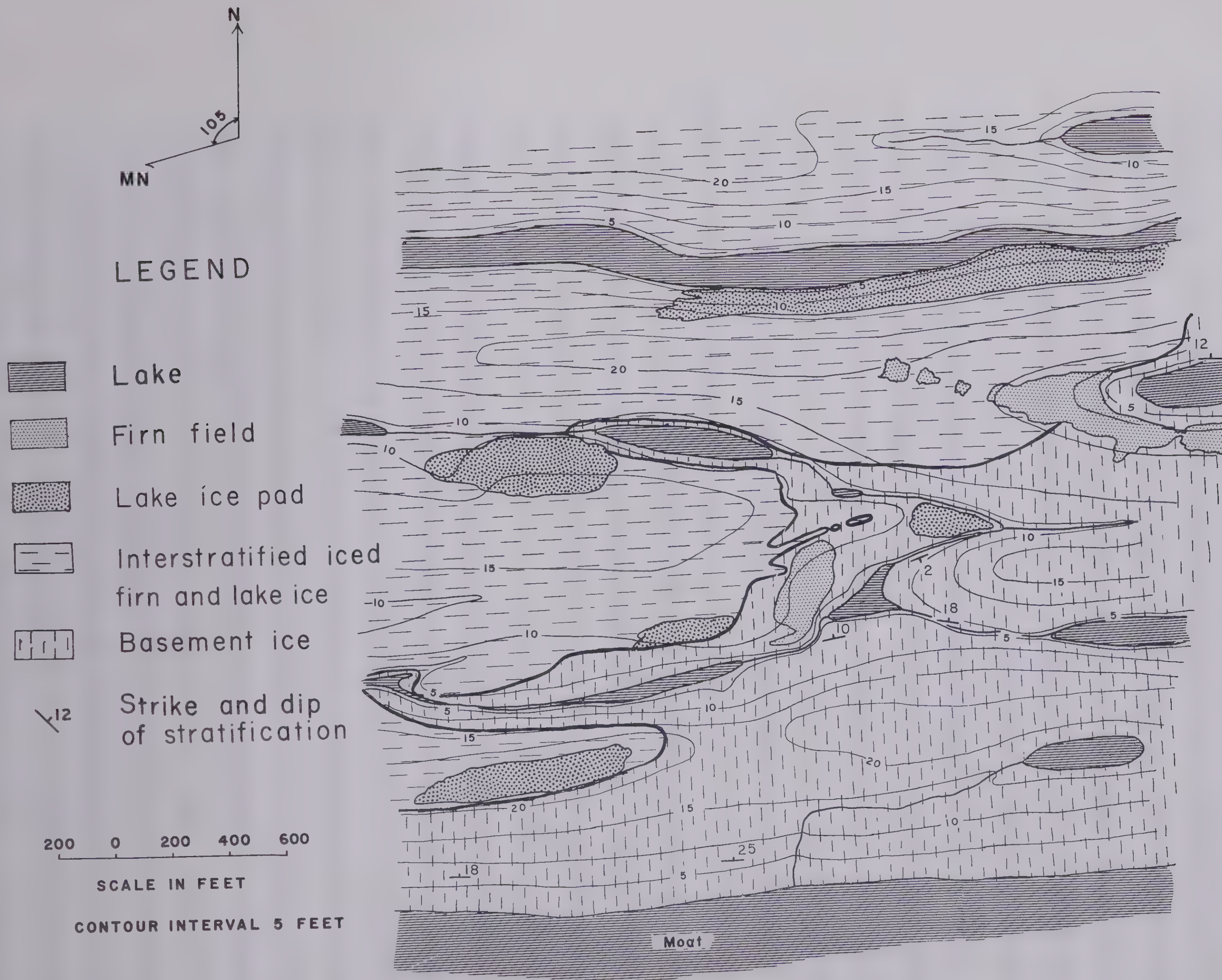

Figure 6 Structural-stratigraphic relations of a portion of the Ward Hunt shelf. Area of map is indicated in Figure 2

Structural Features

The general structure of the shelf in the area between Ward Hunt and Ellesmere Islands has already been described. In Figs. 6, 7 and 8 are shown some of the significant smaller-scale relations observable near the Ellesmere moat. A consistent shelf-ward dip of the stratification in the basement ice occurs along the moat edge at Ward Hunt, where it averages 6^{o} to 10^{o}, and along the Ellesmere moat where it ranges from 18^{o} to 35^{o}. The amount and rate of recent upturning of the shelf edge may be calculated approximately (see next paragraph), and from this it is clear that less than 2^{o} of the dip is due to curling-up of the edge owing to differentiatal ablation in the last 1600 years. Hence most of the tilt of the stratification must be due to original dip, or to early deformation. This deformation would predate the unconformity, and probably coincides with a period of minor glaciation during which snow or firn was banked in against Ellesmere Island (cf Hattersley-Smith, 1956a, p. 77). It is significant that if the dips in the basement ice (corrected for subsequent tilt) are projected across the Ellesmere moat, they yield elevations along the shoreline in the range of 52 to 120 meters (mean 75 meters). This is reasonably close to the 60 to 90-meter elevation of a pronounced trim line along the Ellesmere shore (see section in Glacial Geology and Fig. 11), and suggests a tie-in between the trim line and the period of minor glaciation.

Two bits of data provide us with a rude but reasonably consistent estimate of the relative rate of upwarping of the shelf edge. The shoreward edge of the basement ice near southeastern Ward Hunt Island is strewn with marine organisms which include siliceous spongers, pelecypods (5 species), gastropods (3 species), bryozoa (2 species), serpula tubules, fish (2 species), ophiruoids, echinoids, and a sea pen. A 400 $\pm$ 150 year radiocarbon age has been determined on a siliceous sponge from this area (Crary, 1960, p. 43), where the ice (see Fig. 9, section BB') is approximately 15 meters thick.

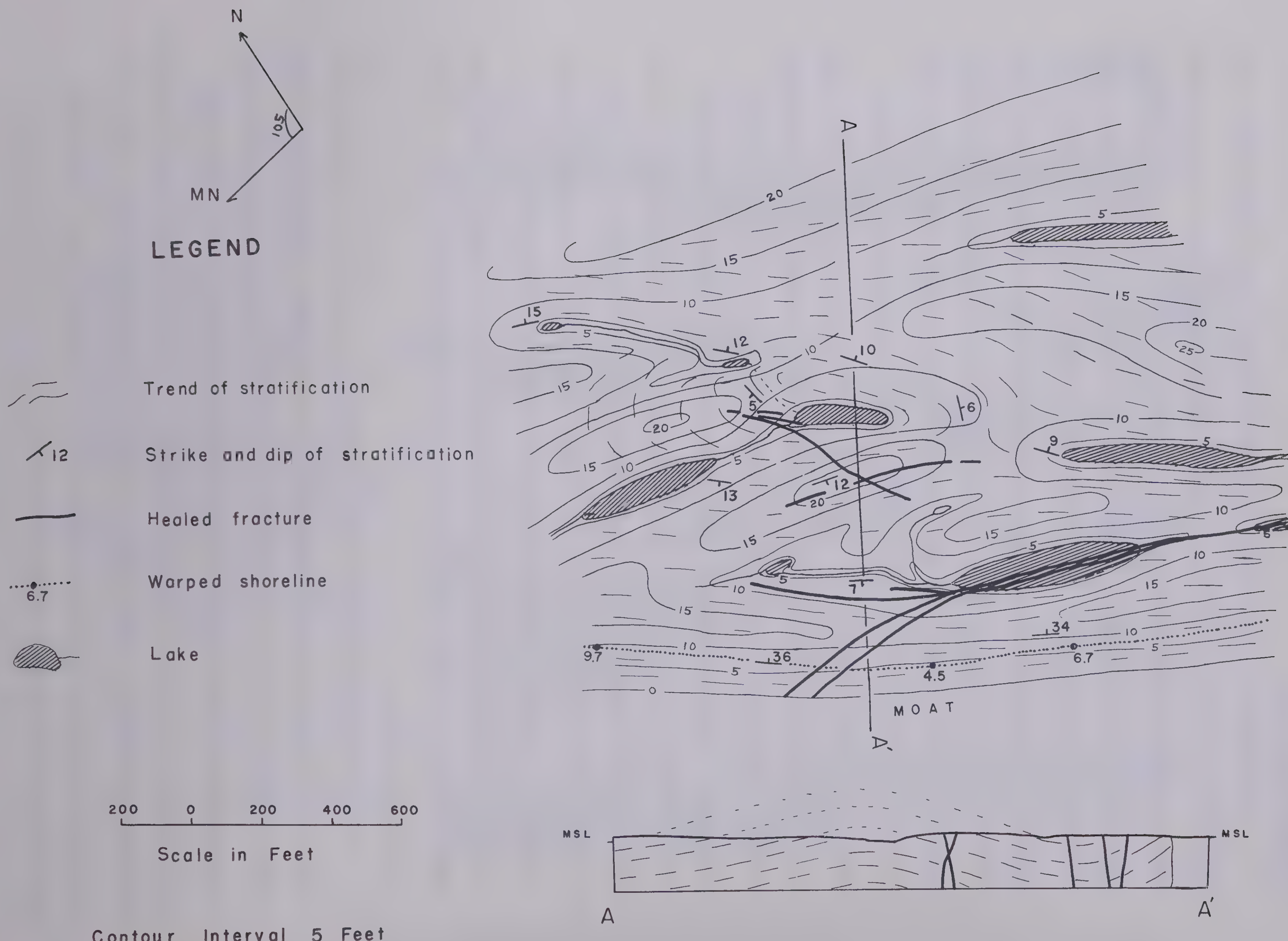

Figure 7. Structures of the basement ice: Ward Hunt shelf. Area of map

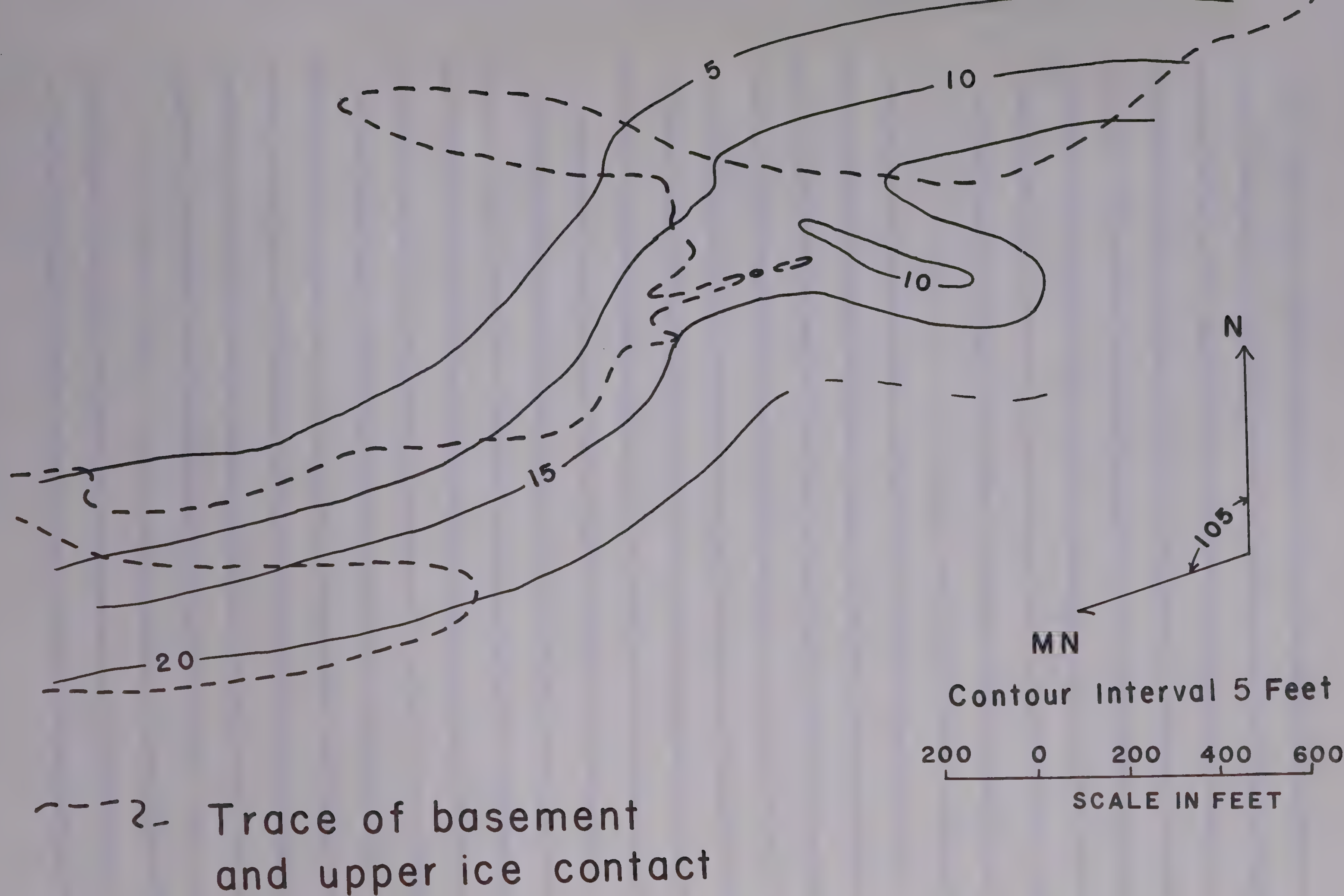

Figure 8 Contour map of the surface of the basement ice; Ward Hunt shelf. Dotted line indicates contact of basement and upper ice units shown in map of Figure 6

Assuming that these organisms have been passed through the ice by a continuous process of freezing at the bottom and ablation at the surface, they have risen at an average rate of one meter in 27 years. Near the Ellesmere moat, it is possible to contour the unconformity surface mapped in Fig. 6 (see Fig. 8); this surface dips northwesterly at approximately $1\frac{1}{2}^{o}$. If the surface was at one time approximately level, and is 1600 years old (Crary, 1960, p. 45) the edge has risen approximately 30 meters in that time, or at a relative rate of approximately one meter in 53 years with respect to the center of the shelf (cf. Fig. 9, section AA').

Stresses other than those representing plastic rebound caused by erosion are obviously necessary to explain most of the structural features in the basement ice. In Fig. 6 (for location see Fig. 2) dip and strike symbols bring out a gentle asymmetric syncline and anticline, and the map of Fig. 7 (in an area 5 kilometers southeast of Fig. 6) shows another asymmetric syncline, and a doubly plunging anticline. Marshall (1960, p. 51) and Cabaniss (oral communication) have both cited deformed basement ice structures in the Colby Bay area of T-3, with dips as high as 70^{o}. Because these folds are developed only locally on the Ward Hunt shelf and in the near-shore areas of the basement, it is logical to conclude that they were caused by the compressive effects of valley glaciers which advanced toward the shelf during or subsequent to the formation of the basement. These folds as noted previously pre-date the surface of unconformity marking the base of the upper portion of the shelf. Their development probably coincides temporally with the aforementioned period of minor glaciation along northern Ellesmere, during which time small valley glaciers undoubtedly coalesced with the firn near the Ellesmere shore, and pushed against the then-existing Ward Hunt shelf, curling up and locally folding its landward edge.

In contrast to the basement ice, the upper firn and lake ice exhibit no pronounced deformational structures. The maximum dip observed in the

stratification of the iced firn was 20°, but this was abnormal; throughout most of the shelf dips are too low to be accurately measured. Dune bedding has been reported by Marshall (Hattersley-Smith, 1957, p. 47) (probably in basement ice) in Disraeli Fiord, but was not observed by the writer within the upper iced firn, and is evidently rare. It is also not recognizable in the series of detailed profiles across several T-3 ridges published by Crary (1958, Fig. 19).

The tilting of the upper iced firn of the shelf could be expected, on an areal basis, to roughly parallel the tilting of the unconformity at its base. It has already been pointed out that this tilting, in general, amounts to less than $1\frac{1}{2}^{\circ}$. Nevertheless, this slight amount of deformation, which is fundamentally controlled by differential ablation, accounts for the major structural map pattern on the shelf as outlined by Figure 2.

The contour map of the unconformity brings out another significant feature - the low relief (slightly more than 3 meters) and generally smooth surface of the unconformity. More maps such as Fig. 8 would be desirable to prove the point, but the tentative inferences are that (1) the ridge and trough pattern characteristic of the present-day shelf must have been very poorly developed during the ablation cycle represented by the unconformity, and (2) the basement ice may then have been only half as thick as the present shelf, since its relief was only half as great.

Recent deformation structures on the shelf are recognizable in (1) active or rehealed fractures, (2) warped shorelines on the ice near the Ellesmere moat, and (3) ice-thrust structures, developed during the 1960 freeze-up along the east side of the Ward Hunt moat. Two of the above-mentioned structures are shown in the map of Fig. 7.

The warped shoreline is identifiable, near the moat, as a clearly distinguishable break (transecting the stratification) between rough well-layered cryoconite-pitted basement ice on the upper slopes and smoothed base-

ment ice on the lower slopes. The shorelines fluctuate in elevation between moat level and 4 meters, and are developed only locally, particularly in areas where master streams debouch from the shelf. They are interpreted, therefore, as very young structures, caused by differential plastic rebound in areas of rapid erosion. These areas are also (not unexpectedly) somewhat thinner than usual; as calculated from their mean elevations, they average two-thirds of the normal shelf thickness.

Rehealed fractures are identifiable by their characteristic comb structure, with large basal platelets (up to 15 cm. in width) standing vertically normal to the fracture walls. Except locally along the Ellesmere moat these fractures are rare, and were observed in only one locality in the upper ice units. Active and rehealed fractures are tensional in nature, and there has been repeated rupturing of the shelf along the major fracture system of Figure 7. There are at least two possible explanations for the fractures, neither of which is completely satisfactory, and both of which are difficult to reconcile with the more obvious evidences of plastic deformation in the shelf: (1) yielding of thinner areas to rapidly applied or locally strong stresses, and (2) reopening or reexhuming of fractures developed in the basement during an early stage of its formation. In this event, glacial push from Disraeli Bay could account for the orientation of the major fracture system.

Overriding of moat ice by basement ice along steeply dipping thrusts near the eastern edge of Ward Hunt Island accompanied the 1960 freeze-up. Underthrusting by the freezing moat ice would appear to be the most likely cause for these faults, but because of tidal action the edge of the moat had not frozen solidly when the thrusts developed. Thus, another mechanism may be driving the shelf toward Ward Hunt, but if so, its origin is obscure.

Surface Morphology

Two aspects of the surface morphology of the Ward Hunt Shelf and of

T-3 which have been discussed rather fully in the literature are (1) the origin of the ridge and trough pattern, and (2) modification of the existing topography. Both of these questions are interrelated.

Crary (1958, p. 25-27), on the basis of correlation of dirt layers in closely-spaced drill holes on T-3, was the first to present convincing evidence that the positions of ridges and troughs on the present surface of the ice island do not coincide with the positions of former ridges and troughs of the build-up cycle in the ice island's history. Subsequently, Smith (1960) presented detailed evidence that both the inversion of relief on T-3 and its general topography were controlled by the albedo of the three major ice types - modern lake ice, old lake ice, and iced firn, the latter being the least resistant and the former the most resistant to erosion. Other things being equal, modern lake ice should eventually form the highest eminences, and iced firn the lowest areas. Smith (op. cit.) concluded that the ridge and trough pattern of T-3 could be ascribed to "structural control by the parallel pattern of the bodies of old lake ice which impart the structural grain to the ice island and presumably to the shelf" (Smith, 1960, p. 58).

Evidences of inversion of relief similar to those described by Smith at T-3 (op. cit.) are abundant on the Ward Hunt Ice Shelf, and need no repetition here. However, inasmuch as Smith did not carry out albedo determinations at T-3, an effort was made to obtain quantitative radiation data on the various ice types of the Ward Hunt area. The readings are recorded in Table 2 (below). They were made using a Beckman-Whitley radiometer (Model N 188-1) for net radiation, and a Moll solarimeter (Model Kipp) in the direct and inverted positions for the albedo determinations. The data in the table are spot readings only, taken in late August, and should be regarded in this light.

Table 2

Albedo Values for Varying Ice Types; Ward Hunt Shelf

Ice Type	Overcast, low fog, windy			Scattered overcast low fog			Clear, bright windy		
	Net radiation langleys/min	Incoming short wave; langleys/min	Albedo (%)	Net radiation langleys/min	Incoming short wave; langleys/min	Albedo (%)	Net radiation langleys/min	Incoming short wave; langleys/min	Albedo (%)
Basement ice (clean)	.078	.109	21	.183	.252	33	.300	.455	2
Basement ice (dirty)	.142	.151	13	.216	.239	12	.362	.468	1
Iced firn (dirty)		.054	30	.261	.340	28	.284	.460	2
Iced firn (clean)							.149	.338	5
Iced firn and lake ice					.248	45	.149	.455	5
Moat ice	.128	.186	42	.204	.266	40	.216	.467	4
Lake ice								.284	5

R. Brian Sagar (oral communication), who carried out systematic radiation measurements at the meteorological site (see Fig. 1) throughout the 1960 summer reports late-season albedos in the range of 55 to 60% for melting ice - the equivalent of "clean iced firn" and "iced firn with lake ice" in the table above. The values listed in Table 2 are in line with Smith's qualitative estimates. The data indicate that the basement ice, in general, should ablate more rapidly than any other type, and that the iced firn should have a high or low ablation rate, depending on the quantity of dust on its surface. Lake and moat ice should waste more slowly than some varieties of iced firn; their resistance to erosion is enhanced by the high porosity resulting from candling.

The albedo factor is clearly of some significance in modifying the shelf topography, but whether it is the major control appears doubtful. In the area shown in Figure 6 the drainage pattern is superimposed without modification across several ice types; and the area of homogeneous basement ice of Figures 2 and 7 shows no breakdown of the basic ridge and trough system. Of the 18 ridges between Ellesmere Island and the Ice Rise (Fig. 9), 9 are underlain predominantly by iced firn, 3 predominantly by lake ice, and 6 by interstratified iced firn and lake ice. The most obvious cases of extensive modification of the shelf topography are the large sheets of modern lake ice (some a few kilometers long) which have been preserved in a few troughs (see Fig. 9) and which are evidently rising (because of less rapid ablation) with respect to the ridges on either side. The key factor in initiating the development of these sheets is the chance sealing off of the lake exit, either by snow drifting, freezing, or a combination of these processes. Once this fundamental event has occurred, the albedo factor may then become important. Comparison of 1952 aerial photographs with field observations of 1960 shows that modern lake ice sheets are relatively unstable; some have disappeared and others have appeared in this 8-year interval.

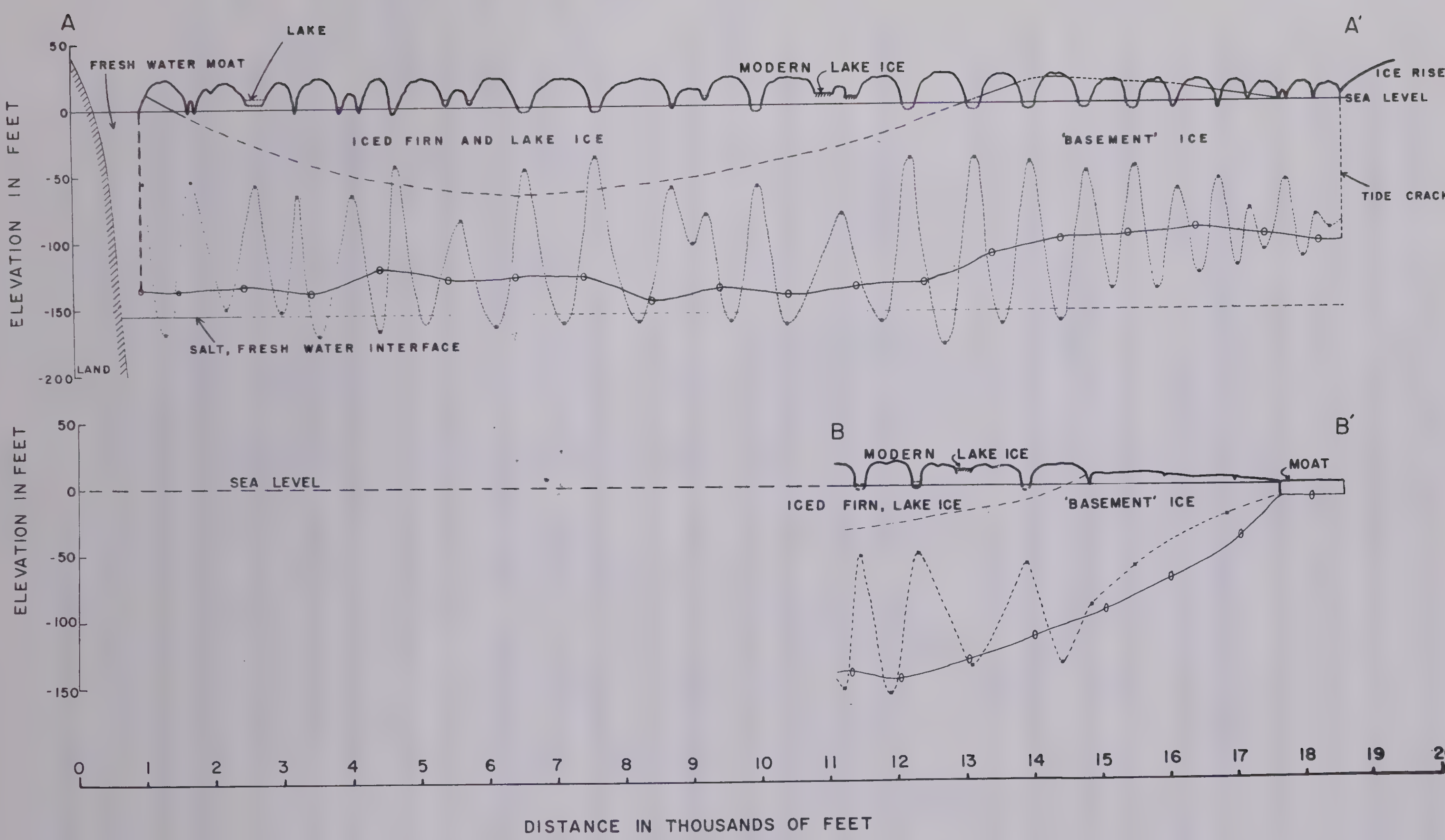

Figure 9 Profile across ridge and trough system; Ward Hunt shelf. Dashed line is projected contact of basement and upper ice units; dotted line is possible bottom configuration, assuming strong compensation; solid line with circles is possible bottom configuration assuming broad areal compensation of the shelf. Vertical scale exaggerated 20 times.

Obvious clues to the origin of the ridge and trough pattern of the Ward Hunt Shelf are obscure. Hattersley-Smith (1957) after considering and rejecting such possible mechanisms as deformation by glacial push, contraction and expansion resulting from temperature changes, pressure of pack ice, and tidal action has concluded that wind action offers the best solution to the enigma. He visualizes an initial series of seif-like linear snow dunes on the shelf. As degradation commences meltwater becomes channelized between these ridges, thus giving rise to a series of parallel lakes. These have been perpetuated during the present ablation cycle on the shelf, and owe their orientation to the predominant easterly or westerly winds along northern Ellesmere Island.

Crary (1960) follows Hattersley-Smith, but emphasizes the action of the prevailing easterly or westerly summer winds in elongating any randomly scattered ponds. Smith (1960) also favors the wind hypothesis, modifying it to account for the bodies of old lake ice which developed during the build-up of the shelf and which now, he believes, impart the "structural grain" to the ice island. Marshall (1960, p. 47) by contrast, suggests that the pattern originated in the basement, through the development of crevasses in floating valley glacier tongues both along hinge lines and parallel to the flow lines of the glacier. The pattern was modified by melt action before the build-up of the upper unit of the shelf.

It is difficult to find convincing proof or disproof of either the Hattersley-Smith or Marshall hypotheses. Rehealed fractures in the basement ice are rarer than one might expect under the glacier-tongue hypothesis, and their distribution seemingly is more related to areas of sharp curvature in the shelf than to any other feature. If, as the core data indicate, the outer half of the shelf is built on a sea ice platform, and lacks the typical "basement" and dirt-strewn unconformity, modification of the Marshall hypothesis would obviously be necessary.

As pointed out previously, good examples of dune bedding in iced firn are extremely rare, and the one example cited (Hattersley-Smith, 1957, p. 42) is evidently from an area within the basement ice. The Markham Bay reentrant has an incipient ridge and trough pattern with a much shorter wavelength than that of the shelf. This area has been taken by Hattersley-Smith (1947, p. 42) as an illustration of seif dune development in firn resting on a sea ice platform. Marshall (1955, p. 112) described firn in the upper foot of a core in the reentrant, but the 1960 core studied by Ragle and Blair (oral communication) showed no recognizable firn; the reentrant is apparently a mass of sheared, jumbled sea ice. The origin of its incipient ridge and trough pattern cannot, therefore, be considered as confirming the wind hypothesis.

Somewhat similar questions might be raised concerning the ridge and trough pattern on lake ice in a valley 15 miles south of the head of Ayles Bay, Ellesmere Island, cited by Hattersley-Smith (op. cit.) as buttressing the wind hypothesis. The ridge and trough pattern here could be due to wind action but because active (?) glaciers hem in the lake on both ends, it is also possible that compressive forces may have induced tensional fractures in the lake ice surface.

Another suggestion by Hattersley-Smith (1957) may deserve more support than he has given it. At Yelverton Bay, he has noted that pack ice pressing and accreting at the edge of the shelf produces "hedges", and he has proposed that these may represent a possible early stage in the ridge and trough development. Dr. H. Lister (oral communication) has independently arrived at a somewhat similar conclusion. He noted, during the 1960 season, the gradual modification of the recently accreted pack ice into a smoothed but ridged topography, and pointed out to the writer the considerable difficulty one experiences in clearly differentiating such newly accreted portions of the shelf from other somewhat older areas on its outer periphery. Crowley's

(1961, Fig. 2) profile brings out the fact that as much as 1.2 kilometers of the outer portion of the shelf consists of sea ice whose upper contact dips gently landward, and flattens out under the main portion of the shelf at a level (22 to 27 meters) consistent with sea ice - upper ice contact picked up by Ragle and Blair in their ice core investigations

A composite origin for the ridge and trough pattern appears to the writers to offer the most satisfactory synthesis of the evidence. Crevasses in floating glaciers moving out into fiords undoubtedly may cause a ridge and trough pattern, but the structure of the outer shelf indicates that some additional mechanism - most probably the modification of accreting pack ice - must be of major importance. The wind hypothesis lacks convincing evidence. The predominant easterly and westerly winds tend to modify and perpetuate the drainage system, by piling up waters at either ends of the lakes, but evidence of seif-dune formation as the fundamental control on the drainage system appears to be difficult to substantiate. Whatever the cause of the ridge and trough topography, the shelf stratigraphy implies that this topography was present even during the accretionary cycles of the shelf's history. In the present cycle of accelerated ablation, the deep superimposition of the drainage pattern has obscured many of the clues to its origin.

Subsurface Morphology

The configuration of the underside of the shelf is somewhat speculative. Hattersley-Smith (1957, p. 33) has suggested that because the shelf is floating "it may be expected to be proportionally thinner beneath the troughs and thicker beneath the ridges." Seismic data (F. Crowley, verbal communication) likewise suggest some such type of compensation locally, particularly in the area near Ellesmere Island. His profile across the shelf, however, (Crowley, 1961, Fig. 2) would indicate a general lack of local compensation.

It is obvious, of course, that the shelf cannot be completely compensated,

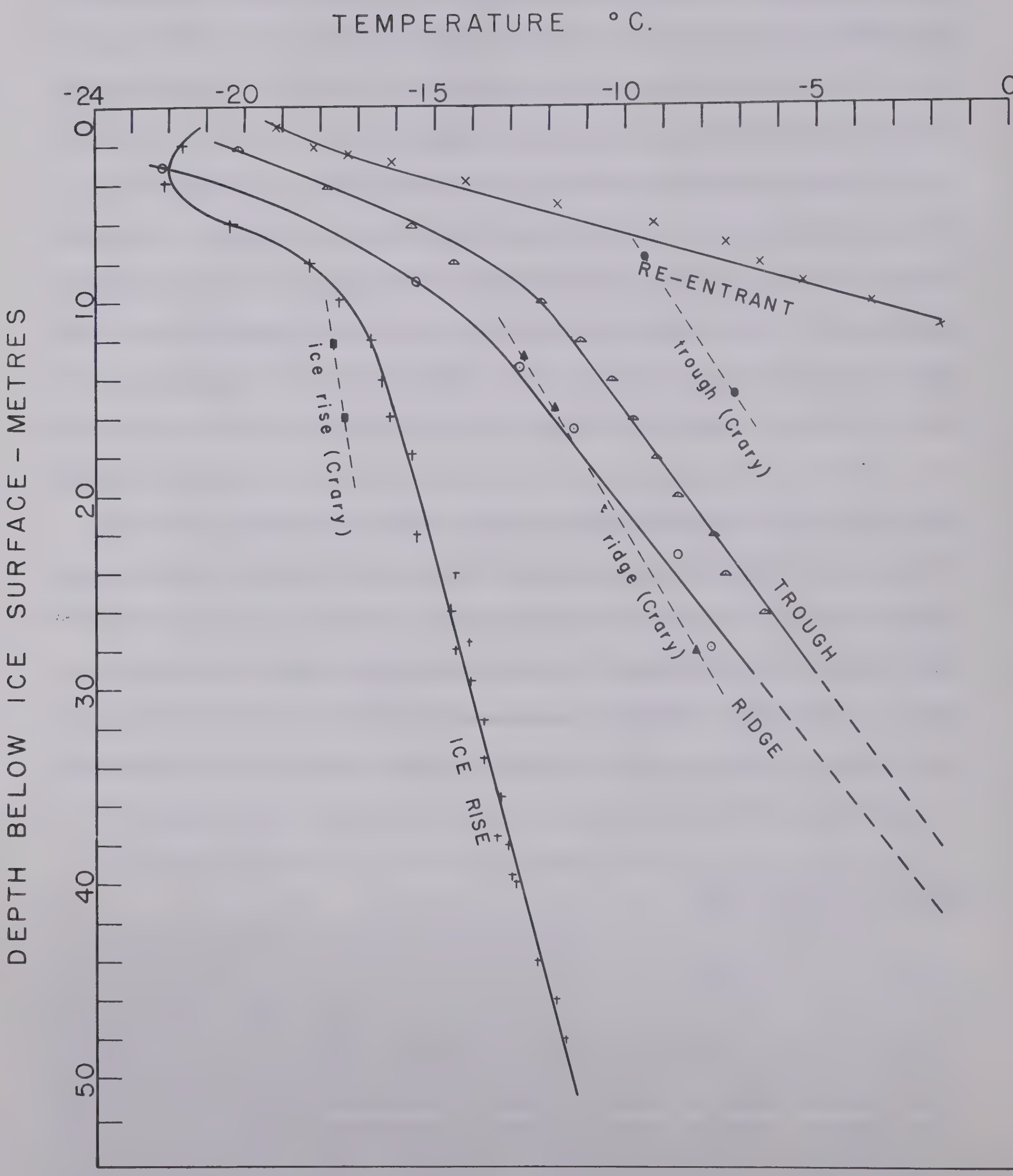

Figure 10 Thermal profiles through Ward Hunt ice shelf. Reentrant, trough, ridge and upper portion of ice rise temperatures determined by thermistor readings; lower portion of ice rise core by lag thermometer. Data chiefly after Ragle, Blair, and Molholm

for in this case it would be thin to zero thickness at each of the troughs which reaches moat level (cf. Fig. 9). Thermal profiles in holes drilled into a ridge and a nearby trough (Fig. 10) have essentially parallel slopes, and project downward to the -1.8° C isotherm (the temperature of sea water) at a difference in depth which corresponds closely to the elevation difference of the holes at the surface. This would imply an almost horizontal undersurface for the shelf.

Two possible bottom configurations for the shelf have been calculated from the surface profile data of Figure 9, using an ice density of 0.905 (Crary, 1956, p. 12). The solid line is based on an assumption of broad areal compensation (over a span of 650 meters), and the dotted line assumes local compensation for areas above and below 3.6 meters (the approximate mean elevation of the shelf). The drill core and thermal data support the broad areal type of compensation. Additional evidence favoring this interpretation is the fact that a water sampler was twice snagged at a depth of 46 meters, at what appeared to be the bottom edge of the ice along the Ellesmere moat. This is within 1/3 meter of the calculated ice thickness, assuming broad areal compensation.

The temperature readings plotted in Figure 10 were taken by thermistors in the ridge, trough, and reentrant cores, but by lag thermometer in the lower part of the ice rise hole. If the straight line portions of the ridge and ice rise temperature curves are projected back to the surface, they meet at -18°C, - the mean annual temperature. Crary's (1956, p. 39) measurements of thermal profiles on the ice rise yielded corresponding values of -17.7°C to -17.3°C. As pointed out by Crary (op. cit.) the latent heat given off by the freezing of water in a trough will cause a parallel offset in the thermal profile of the trough with respect to that of a nearby ridge (cf. Fig. 10).

Glacial Geology

The glacial geology of northern Ellesmere Island has been reported upon extensively by Hattersley-Smith (1954, 1955, 1956 a, b, c; 1957 a, b, and 1958). There is abundant field evidence supporting his thesis that a major cycle of glaciation preceded the development of prominent raised beaches along Ward Hunt (at 43 meter elevation) and Ellesmere Islands (elevation 61 meters), and that the ice shelf post-dates the beaches. The latter are known to be 7200 years old (Crary, 1960). Hattersley-Smith also recognizes (1956, p. 77) a "recent development of snowdrifts (now dissipated) merging with the ice shelf in the lee of cliffs, where now there is a moat; only on such an assumption is it possible to account for the large boulders of country rock on the edge of the ice shelf." These "snowdrifts" are assumed to have formed at a time of minor and local glacial readvance, during the same period in which a small glacier encroached upon that portion of the shelf which has since become T-3.

The most arresting feature of the present coastline of northern Ellesmere Island is a trimline at an elevation of 60 to 85 meters above sea level (cf. Fig. 6) presumably coinciding with the former level of snowdrift ice. As pointed out by Hattersley-Smith (op. cit.), this trimline is generally marked by large heaps of talus and morainic material. It has also been pointed out, in a preceding section, that the elevation of the trimline coincides reasonably well with the projection of the stratification in the basement ice across the Ellesmere moat. The trimline thus also evidently predates the ablation cycle and major unconformity on the shelf, estimated to be 1600 years old (Clary, 1960, p. 45).

In the areas 8 and 13 kilometers west of Camp Creek two prominent benches, cut in bedrock, slope gently seaward from elevations of approximately 89 meters. Despite their great geomorphic resemblance to wave-cut platforms, the surfaces of these benches are strewn with poorly sorted

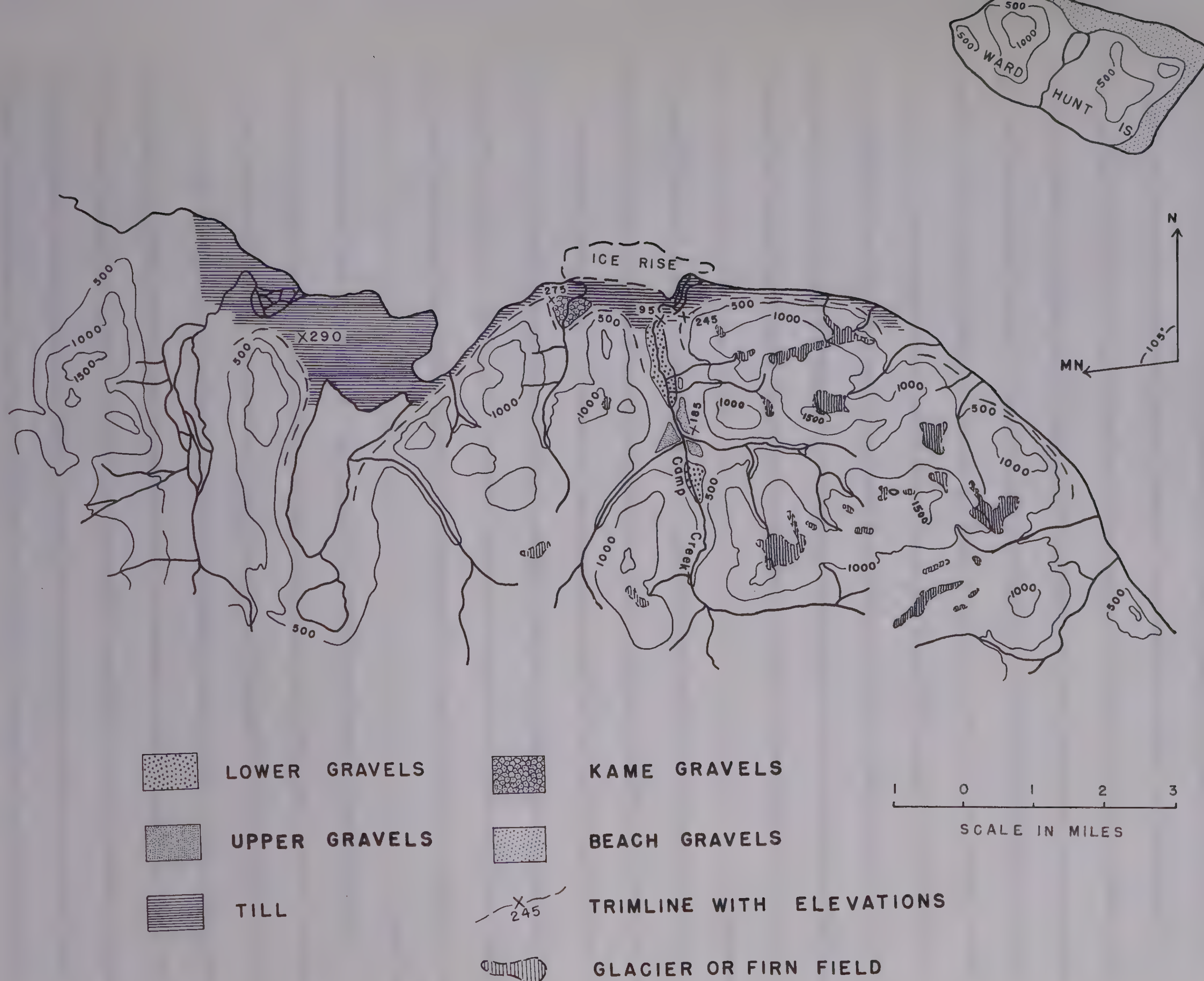

Figure 11 Sketch map of surficial geology, Camp Creek area, northern Ellesmere Island

angular morainal (?) material, are non-fossiliferous, and are marked locally by closed ice-melt (?) depressions up to 25 meters in diameter. These characteristics contrast sharply with the easily-recognizable and well-preserved beach features along northern Ward Hunt Island.

A kilometer and a half west of Camp Creek, a major stream debouches into a flat area of till behind a small ice rise (see Fig. 6), before turning westerly and emptying into the moat. The mouth of the stream valley, immediately south of the till, is plugged with a 45 to 60-meter thickness of fluvio-glacial sands and gravels, pitted by small ice-melt depressions. The gravel surface is generally accordant at an elevation of 84 meters - in this area, the approximate elevation of the trimline. The deposit is evidently an ice-contact kame, formed at a time when ice (or iced firn) blocked the northern shore of Ellesmere Island, ponding meltwaters emptying from the local streams.

The small ice-rise north and west of the mouth of Camp Creek (Fig. 11) conceivably could be a vestige of this ice apron which banked in against Ellesmere during the period of kame formation. However, it consists entirely of horizontally stratified iced firn, similar to that in the upper portion of the shelf, and is evidently younger than the basement ice, and the kame. Whether the ice rise contains a core of basement ice could only be determined by drilling.

The till which now surrounds this ice rise on three sides contains numerous chips, but very few complete shells, of the same pelecypods (identified by Hattersley-Smith as <u>Saxicava</u> <u>arctica</u>) which are found intact in the beach deposits at Ward Hunt Island. One of the best collecting localities is along the southwestern perimeter of the ice rise, where one may occasionally reach beneath the ice to extract chips of the fossils. The fragmentation of these fossils, and the presence of till rather than beach deposits along the northern Ellesmere shore imply to the writers that the ice apron must have

been something more than mere snowdrift; it must have had some motion, and many of the characteristics of a glacier. We have already cited (in the section on Structural Relations) the rather impelling evidence for local glacial push to explain the anticlinal and synclinal folds in the basement ice. There is every reason to suppose that the glaciation related to the kame deposits and the trim line is identical to that which caused the deformation of the basement ice. This glaciation therefore pre-dates the shelf unconformity (approximately 1600 years ago), and would also pre-date the formation of the upper portion of the shelf.

It is clear that there have been three periods of firn accumulation or glaciation on northern Ellesmere Island: (1) major glaciation prior to 7200 years ago, (2) minor glaciation coinciding with the formation and deformation of the shelf basement; waning stages of this glaciation are marked by fluvioglacial deposits along northern Ellesmere, and by an unconformity at the top of the deformed basement ice, and (3) renewed firn accumulation in a period dating from approximately 1600 to 400 years ago (Crary, 1960, p. 44-46).

Camp Creek itself exhibits unique geomorphic relations which bear upon the interpretation of the glacial geologic history. Near its mouth the stream drops over a series of falls, 27 meters high, onto a small floodplain approximately at sea level. The small area of this floodplain, the large amount of non-reworked till surrounding it, and the active cutting of Camp Creek into the eastern side of the small ice rise all point toward recent uncovering of this area, as well as rapid ablation of the ice rise.

Above the falls, which are controlled by resistant basaltic tuff beds of the M'Clintock formation, is a flat alluviated gravel plain, a mile and a third long. On the east side of the valley a mile south of the falls, and 12 to 16 meters above the gravel plain, is an area of poorly sorted silt and pebbles in which Hattersley-Smith (1956, p. 19) collected forams (one species), pelecypods (three species, including <u>Saxicava</u> <u>arctica</u>) and gastropods (two

species). All these fossils are marine, and occur at approximately the same elevation as the pelecypods on the Ward Hunt raised beach. The Camp Creek fossils, however, do not occur in well-sorted beach material, and the deposit has evidently been somewhat disturbed, possibly by soilfluction or by slight downslope and downstream movement of the firn which occupied the valley during the second glacial cycle.

Three kilometers above the mouth of Camp Creek, at the confluence of its major tributaries, (see Fig. 10) are well-reserved but deeply incised remnants of a high terrace surface at an elevation of 55 to 68 meters, cut partially on vertically dipping bedrock and partially on moraine, and capped with coarse fluvio-glacial (?) gravel containing well-rounded cobbles and boulders. A half mile upstream are two additional terraces, at elevations of 49 and 40 meters; these are clearly stream-cut, younger than the highest terrace, and incised on morainal material. The high terrace slopes gently downstream from an elevation (near the stream junction) of 68 meters - approximately the same elevation as the well-preserved raised beaches along the west shore of M'Clintock Fiord (Hattersley-Smith, 1956, p. 111).

The origin of all three terraces is somewhat speculative, but may be reconstructed as follows. Following the first widespread Ellesmere glaciation, the sea encroached up Camp Creek, developing a local beach and probably cutting a small platform near the present high terrace. As melting commenced, following the second local glacial cycle, iced firn plugged the lower reaches of Camp Creek, ponding a small body of water in the valley at an elevation close to 61 meters. (This event coincided in time with the period of kame formation in the next valley to the west.) Fluvio-glacial streams entering the lake spread their coarse detritus near the shoreline, but most of the fines escaped along marginal meltwater channels. As the lake gradually lowered, a gravel-cupped terrace was developed at the approximate location of the former marine platform. Rather rapid ablation of the firn allowed

water level to drop below a 49 meter elevation; at this point a bedrock obstruction in the valley controlled local baselevel sufficiently long to allow formation of the intermediate terrace. When this obstruction was removed, a second bedrock rib controlled the baselevel at 40 meters for a long enough time to allow the cutting of the lowest terrace. Present baselevel (27 meters) is controlled by the falls near the mouth of Camp Creek.

There are some points of interest to be added to the general discussion of the glacial geology, because of their implications concerning rates of erosion. If Crary's (1960, p. 45) assessment of numerous rediocarbon dates is correct, the basement ice near Ward Hunt may not have commenced to form until 3000 years ago, an ablation cycle culminated 1600 years ago, and the last cycle of firm accumulation terminated 400 years ago. The evidence we have cited is not inconsistent with the surprising suggestion that all three terraces on Camp Creek are less than 1600 years old, and possibly much younger; in any event they must be younger than the 3000-year age assigned by Crary (op. cit.) to the beginning of the Ward Hunt Ice Shelf.

Summary History

A recapitulation of the glacial geologic and shelf history would be as follows:

(1) Widespread glaciation covering much of Ellesmere Island to elevations of at least 760 meters, and overdeepening fiords to depths of 860 meters (F. A. Crowley, oral communication) maximum ice thickness of at least 1620 meters; land depressed under the glacial load.

(2) Amelioration of climate, and development (as the land rebounds) of beaches now found at various elevations between 180 and 43 meters (Christie, 1957, p. 28). Beaches at this lower level developed approximately 7200 years ago.

(3) Gradual deterioration of climate, and commencement of formation of ice shelves along northern Ellesmere 5500 to 3000 years ago (Crary,

1960, p. 46). Landward portion of shelf probably partly glacial ice; seaward portion sea ice. Local glaciation.

(4) Amelioration of climate, partial disintegration of shelf and formation of heavy dirt band 1600 years ago. Terraces cut and kames formed on Ellesmere Island. Shelf thins and shrinks back to a width of 6 or 8 kilometers.

(5) Third cycle of firn accumulation, and second stage of shelf growth terminating about 400 years ago. Shelf attains width of at least 18 kilometers.

(6) Gradual ablation and disintegration of shelf, particularly during the last 60 years.

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